

Distributed Dynamic-Strain Sensing Based on Brillouin Optical Correlation Domain Analysis

Weiwen Zou, Zuyuan He, and Kazuo Hotate,

Department of Electrical Engineering and Information Systems, The University of Tokyo,

7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

Tel:81-3-5841-5779, Fax:81-3-5841-5863, E-mail:zou@sagnac.t.u-tokyo.ac.jp

Abstract: We study the influence of the integral time constant of signal processing in a modified Brillouin optical correlation domain analysis system to the interrogated strain. The synchronization control of the microwave synthesizer, the function generator and data acquisition enables 5-Hz entire distributed sensing with a capability of detecting 2-Hz distributed dynamic strain.

Keywords: Fiber optics sensors, stimulated Brillouin scattering, dynamic strain

1. INTRODUCTION

High-speed fiber-optic distributed sensing is required for structural health monitoring applications. Recently, a novel scheme for modifying a Brillouin optical correlation domain analysis (BOCDA) system was proposed to enhance the speed of the entire distributed sensing [1]. In the scheme, the distributed Brillouin interaction, called as Brillouin trace, was continuously mapped per pump-probe frequency offset. Further, an analog signal processing unit with no limited update rate was adopted to demodulate the optical output of the modified BOCDA system. It was estimated that the entire distributed sensing speed [1] could be much faster than those of the previous schemes [2-3] in which the local Brillouin gain spectrum (BGS) as well as the local Brillouin frequency shift (BFS, ν_B) were repetitiously measured after resetting the frequency modulation parameters to the laser source.

In this paper, we study the dependence of the interrogated strain on the integral time constant (τ_2) during processing the output signal of the modified BOCDA system. By employing a new lock-in amplifier (LIA) with 85-MHz update rate and minimum 2- μ s τ_2 , we can detect the distributed static strain on 5-cm fiber portions along a 50-m fiber under test (FUT) even for a small period ($T_{fm} = 2$ ms) of linearly-sweeping the modulation frequency (f_m). It is successful to diagnose the distributed dynamic strain till 2 Hz when we synchronize the swept f_m and the ramp-swept microwave synthesizer together with recording the Brillouin traces.

2. EXPERIMENTAL DETAILS

The optical configuration of the modified BOCDA system was explained in [1]. The pump and probe waves counter-propagating along a polarization maintaining FUT are

equally divided from the same laser source that is under a sinusoidal frequency modulation (FM) via a function generator. The FM frequency (f_m) and depth (Δf) determine the nominal measurement range (d_m), spatial resolution (Δz) and sensing number (N_s) as follows [4]:

$$d_m = \frac{c}{2n_{eff}f_m}, \Delta z = d_m \frac{\Delta\nu_B}{\pi\Delta f}, \text{ and } N_s = \frac{\pi\Delta f}{\Delta\nu_B}, (1),(2), \text{ and } (3)$$

where n_{eff} (~ 1.446) is the effective refractive index of the FUT, c is the light velocity in vacuum, and $\Delta\nu_B$ (~ 30 MHz) is the Brillouin linewidth.

The FM Δf (~ 10 GHz) is fixed; the FM f_m (~ 1.95 MHz) is automatically swept in a range covering the whole FUT (~ 50 m) for mapping the Brillouin interaction (trace) per pump-probe frequency offset. The nominal $d_m \sim 53$ m, $\Delta z \sim 5$ cm, and $N_s \sim 1050$ are estimated according to Eqs. (1)-(3). The pump-probe frequency offset is decided by a microwave synthesizer whose output drives a single-sideband modulator.

Electronic signal processing

The optical output of the modified BOCDA system representing the entire amplified probe gain (i.e., Brillouin trace) along the whole FUT is transferred to an electronic signal via a photo-detector (PD). The schematic configuration of the electronic signal processing is depicted in Fig. 1. Passed through a ~ 1 -MHz electronic band-pass filter (BPF), the electronic noise at $f_m \sim 1.95$ MHz due to the FM-induced intensity modulation is eliminated. The electronic signal is demodulated at the reference frequency of 1.069 MHz by a new LIA with 85-MHz update rate and minimum 2- μ s τ_2 . The demodulated output from the LIA goes through an electronic low-pass filter (LPF) at 260 kHz and thus is recorded by a 2-MS/s 18-bit-resolution data acquisition card (DAQ).

Influence of the integral time constant

The prepared FUT (~ 50 m) includes two portions (A and B) with just 5 cm in length upon which static and dynamic

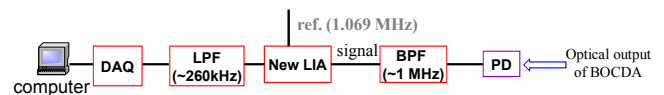


Fig. 1. Schematic configuration of electronic signal processing of the modified BOCDA system. The abbreviations are explained in the text body.

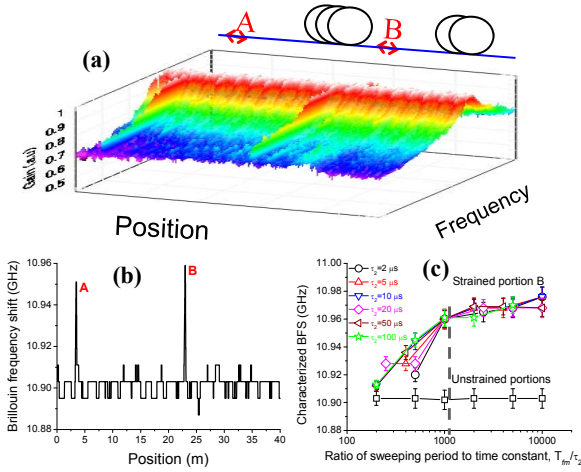


Fig. 2. (a) 3d plot of characterized BGS and (b) distribution of characterized BFS along a 50-m FUT sample with two 5-cm strained portions A and B when $T_{fm}=2$ ms and $\tau_2=2$ μ s. (c) Dependence of the characterized BFS at the portion B or an unstrained portion on the ratio of T_{fm}/τ_2 for different τ_2 .

strain can be applied. Figure 2(a) illustrates the measured 3d BGS when the period of sweeping FM frequency is $T_{fm}=2$ ms and the integral time constant of the LIA is $\tau_2=2$ μ s. Polynomial fitting to the measured 3d BGS provides the distribution of the characterized BFS as plotted in Fig. 2(b). The BFS increases induced by the applied static strain (~ 1500 μ e) at two portions A and B are clearly diagnosed.

For different T_{fm} , we repeat the above measurements. The characterized BFS at the portion B and an unstrained portion in the FUT are summarized in Fig. 2(c) where the measurement accuracies (~ 7 MHz) are expressed by the error bars. When the ratio of T_{fm}/τ_2 is less than the nominal sensing number of $N_s=1050$, the characterized BFS suddenly decreases, which corresponds to a reduced strain value. In other words, the nominal sensing number N_s defined in Eq. (3) or the nominal spatial resolution Δz defined in Eq. (2) is valid only when $T_{fm}/\tau_2 > N_s$. This is because if the integral time constant τ_2 is longer than T_{fm}/N_s then the characterized BFS (i.e., interrogated strain) denotes an averaged value over a segment longer than the nominal Δz . The above dependence is also studied for other τ_2 ($=5, 10, 20, 50$ or 100 μ s) as shown in Fig. 2(c), showing the same behaviour as that of $\tau_2=2$ μ s.

Detection of distributed dynamic strain

There is rather long time (>10 ms) for the microwave synthesizer to reset the microwave output, that is, the pump-probe frequency offset ν . To overcome this problem, we propose a synchronization control scheme as depicted in Fig. 3. Both the pump-probe frequency offset ν (10.75-11.15 GHz) and the FM frequency f_m are simultaneously swept. The data acquisition is synchronously performed. Assuming the effective number of the frequency offset ν as N_v , the period of sweeping ν should be $T_v = (T_{fm}+1) \times N_v$ where 1-ms dead time of the function generator has been considered. The period of mapping all BGS along the FUT is decided as:

$$T_{BGS} = (T_{fm} + 1) \times N_v + T_v', \quad (4)$$

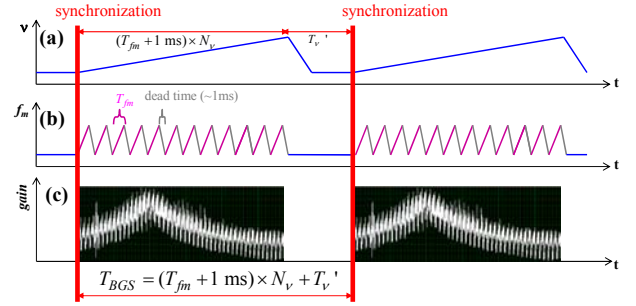


Fig. 3. Synchronized control of (a) ramp-sweeping microwave frequency ν for generating pump-probe frequency offset, (b) linearly-sweeping FM frequency f_m , and (c) recording Brillouin traces.

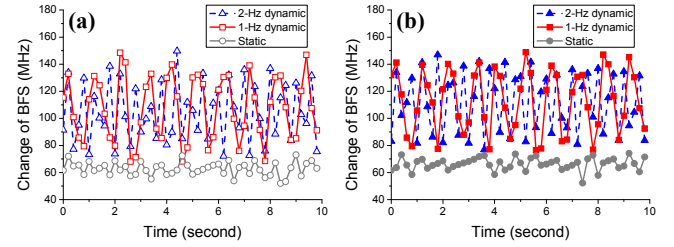


Fig. 4. Detection of distributed dynamic strain at (a) portion A and (b) portion B that are simultaneously applied by a PZT-driven x-stage. Distributed dynamic strain till 2 Hz is successfully detected at an entire distributed sensing speed of 5 Hz.

where T_v' is the dead time of the microwave synthesizer.

When $T_{fm}=2$ ms, $\tau_2=2$ μ s and $N_v=50$, the period of mapping all BGS is $T_{BGS}=200$ ms and the entire distributed sensing speed is 5 Hz. Figure 4 illustrates the characterized BFS changes at portion A and portion B where the same dynamic strain is simultaneously applied by a PZT-driven x-stage. It shows that the distributed dynamic strain till 2 Hz at both portions can be clearly diagnosed.

3. CONCLUSIONS

To correctly measure the applied strain upon a fiber portion at the length of the nominal spatial resolution Δz , the integral time constant τ_2 of lock-in detection in the modified BOCDA system should be smaller than T_{fm}/N_s . An entire distributed sensing speed of 5 Hz with more than 1000 sensing number in a 50-m fiber is experimentally validated, which is capable of detecting 2-Hz distributed dynamic strain.

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